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Lunar Mission Analysis Branch

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PROJECT APOLLO

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By Ronald L. Berry and Robert F. Wiley
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REAL-TIME TARGETING FOR THE APOLLO LUNAR ORBIT INSERTION MANEUVER[a]

By Ronald L. Berry and Robert F. Wiley

ABSTRACT

Real-time targeting for the Apollo Program lunar orbit insertion (LOI) burn is difficult because of the expected approach trajectory dispersions and the constraints on the burn. For certain situations, some of the orbit shape and landing-site target objectives cannot be achieved. Therefore, several impulsive LOI maneuvers are computed, each violating only one target objective. To do this, a series of states along the approach trajectory is generated. At each state, an impulsive maneuver is computed, violating only one target objective. Violations of the objectives are determined at the impulse point from plane geometry and simple orbital mechanics. The maneuver missing the objective the least is retained and displayed to the flight controller. The flight controller selects a best solution based on the mission status at that time. The guidance constants are then determined by computing a finite burn which matches the orbital parameters of the impulsive maneuver.

INTRODUCTION

The Apollo Program, the United States effort to land two men on the moon and return them to earth, contains several complex vehicle maneuvers requiring accurate, reliable, and flexible real-time guidance targeting systems. One of these is the LOI maneuver which inserts the complete Apollo Spacecraft (command and service module plus lunar module) into a low eccentricity orbit about the moon from a hyperbolic approach trajectory. Lunar orbit insertion occurs near perilune of the approach hyperbola as shown in Figure 1 and, thus, is always on the far side of the moon with no earth communications possible. Lunar orbit insertion is one of the largest planned maneuvers in the Apollo lunar mission, requiring a ΔV of approximately 3000 ft/sec. Acceleration during the burn varies from about 7 to 10 ft/sec^2, the burn time is usually between

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380 and 400 seconds, and the burn arc relative to the center of the moon is approximately 20°. A small plane change, generally less than 6°, is associated with LOI. The exact magnitude of the plane change is a function of launch time and of the lunar landing site. The target objectives of the LOI burn and the severe constraints under which the maneuver must be performed give rise to a difficult real-time guidance targeting problem.

The solution to this problem is in two parts. The first part consists of establishing a lunar approach geometry such that an LOI maneuver to the target objectives is feasible. This is accomplished by the preflight mission design and the translunar injection and midcourse correction maneuvers targeted in real time (Fig. 1). The second part consists of the LOI targeting proper; that is, the ground-based computer logic that defines a lunar orbit that best satisfies the target objectives and then calculates the guidance constants to steer into this lunar orbit. If the translunar injection or the midcourse correction maneuvers were executed

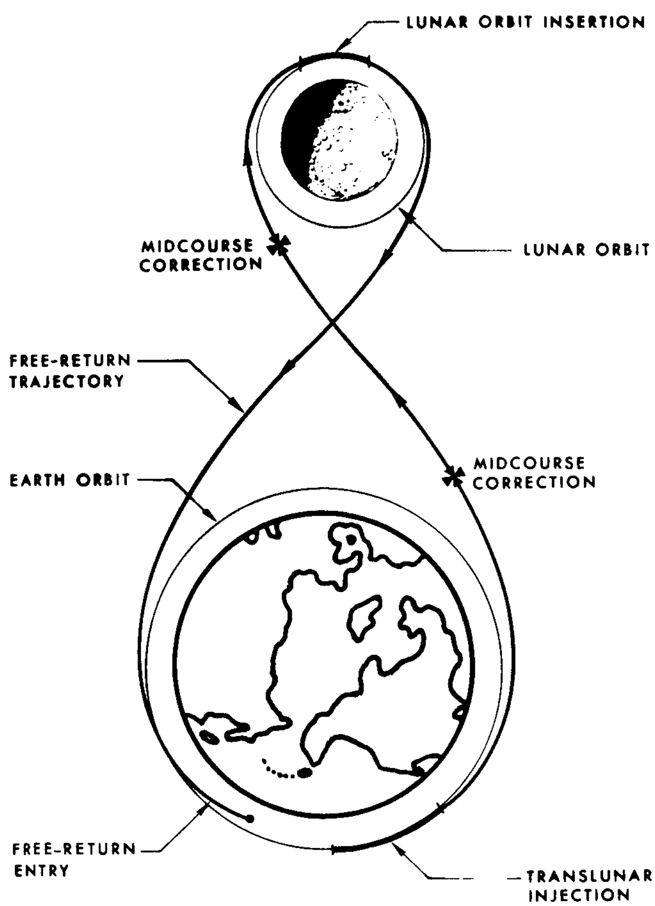

Figure 1. Translunar mission profile.

perfectly, the second part of the targeting procedure would be trivial. However, expected execution errors and state vector uncertainities make complex LOI targeting logic a necessity. This paper is concerned with the second part of the solution of the LOI targeting problem and, in particular, the definition of the lunar orbit.

LUNAR ORBIT INSERTION TARGET OBJECTIVES

There are three basic LOI target objectives (or desired end conditions). These are a lunar orbit shape (apolune and perilune altitudes), a lunar orbit plane that passes over the landing site after a specified number of revolutions, and an approach azimuth to the landing site within a specified range. Within this specified range of azimuths, there is one particular azimuth that is preferred over the others. Thus, in this paper, the landing site approach azimuth will be considered as one objective comprising a preferred azimuth and acceptable azimuths. Landing site objectives (as used in this paper) will mean the passage over the landing site with an acceptable approach azimuth. Together these three target objectives define a set of acceptable lunar orbits in terms of shape and planar orientation. Note that the specific orientation of the line of apsides of the target orbit is not an objective.

The base lunar orbit for the Apollo lunar mission is presently a circular orbit of 60-n. mi. altitude. The 60-n. mi. circular orbit objective resulted from a performance requirement trade-off between the command and service module and the lunar module and a desire to simplify the targeting and operational procedures associated with the required lunar operations of landing, ascent, and rendezvous. The current official flight plan calls for the LOI maneuver to insert the spacecraft directly into a 60-n. mi. circular orbit. However, a flight plan change is being proposed (approval is pending) in which the LOI maneuver would insert the spacecraft into an elliptical 60-n. mi. perilune by 170-n. mi. apolune lunar orbit in order to relax the problems of crew safety and burn monitoring associated with the current plan. In the proposed plan, the LOI maneuver would be followed (two revolutions later) by a small coplanar circularization burn to achieve the desired 60-n. mi. circular orbit. For the purpose of this paper, it is assumed that the proposed change will be adopted.

The specified range of approach azimuths to the landing site must satisfy two requirements. First, the range must be acceptable from a spacecraft performance standpoint; that is, the fuel penalty must not be too severe for the maneuvers required to set up the lunar module descent, ascent, and rendezvous maneuvers and to return to earth (transearth injection). Secondly, the lunar surface terrain directly underneath an approach path to a landing site must be smooth enough to allow satisfactory operation of the lunar module landing radar for navigation. The acceptable approach azimuth ranges for the latter requirement for each candidate lunar landing site will be determined preflight.

LUNAR ORBIT INSERTION TARGETING CONSTRAINTS

The major constraints on the LOI targeting problem are in terms of fuel requirements, simplicity of the steering law, and burn attitude. The performance capabilities of the Apollo spacecraft are so closely matched by the mission performance requirements that usually very little fuel margin exists on a given day. This margin is the difference between the actual and an inviolable minimum fuel at the end of the mission. Thus, there is considerable incentive to target all major maneuvers such as LOI in as optimum a fashion as operationally possible in order to provide for future contingencies such as increased weight and increased mission ΔV budgets.

The fuel constraint is made more severe by the "free-return" requirement. The translunar injection maneuver is required to be targeted to provide a free-return circumlunar trajectory. The term "free return" means that, theoretically, if no subsequent maneuvers were performed following translunar injection, the spacecraft would circumnavigate the moon and return to a safe reentry at earth (Fig. 1). The free-return trajectory has an associated high cost in both launch vehicle and spacecraft performance. The payload injected on the translunar trajectory is lessened from that of a nonfree-return trajectory; therefore, the amount of fuel the Apollo spacecraft can carry is lessened. Also, the lunar approach hyperbola has a significantly higher energy for the free-return trajectory, thus causing an increase in the ΔV required for LOI.

The second major constraint is the simple guidance and steering law available to the spacecraft because of the limited onboard-computer storage. The steering law drives a velocity-to-be-gained vector to zero, using one of two available methods for computing this velocity to be gained. These methods are Lambert and external ΔV.

Two features of this simple guidance and steering affect LOI targeting. The first concerns the targeting of the guidance. Lambert steering guarantees that the vehicle will pass through a specified target vector at a specified time; external ΔV steering guarantees that a specified inertial ΔV vector will be achieved at a constant inertial attitude. Because the target objectives of the LOI maneuver are not explicit in the guidance constants of either scheme, it is not possible to target by inserting the desired end conditions directly into the guidance system.

Also, there is no onboard program to compute the guidance constants from the desired end conditions. Thus, these required guidance constants must be computed on the ground and up linked to the spacecraft. This, of course, necessitates the LOI targeting logic discussed in this paper.

The second feature of these simple steering laws concerns the type of maneuver the guidance can perform. This maneuver is limited to burns in the vicinity of the common node between the approach hyperbola and desired lunar orbit. In other words, the guidance does not have yaw steering capability (the ability to change orbital planes at some point other than the common node). Figure 2 shows the type of LOI maneuver geometry which could be considered if yaw steering capability were available and shows the type to which one is restricted with non-yaw steering guidance. This limitation is particularly significant when one of the maneuver target objectives is a specified orbital plane, as it is for LOI.

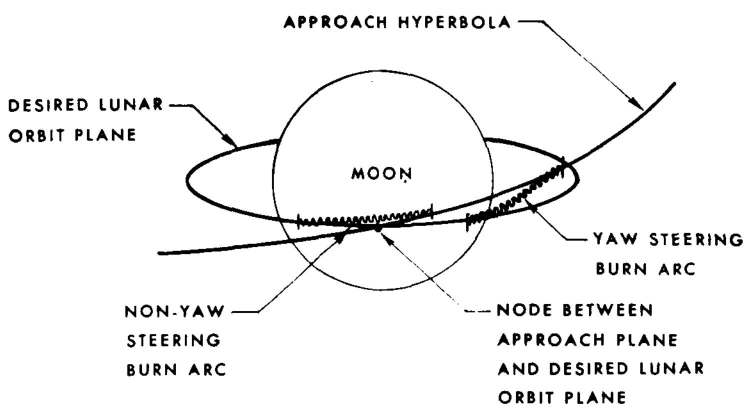

Figure 2. Yaw steering and no-yaw steering geometry.

The last major LOI targeting constraint is in conflict with the first constraint. The last constraint is that the LOI maneuver be targeted and steered to produce an approximate fixed or constant inertial attitude through the entire burn. The purpose of the fixed attitude constraint is to simplify the job of monitoring the burn by the crew, since it is much easier to detect a deviation from a nonvarying nominal burn attitude than it is to detect a deviation from a varying nominal burn attitude. The crew monitoring problem is especially critical for the LOI maneuver since it will not be performed within sight of the earth and thus cannot be assisted by ground support.

Although the fixed attitude constraint results in performance penalties, analysis has shown that these penalities are not sufficiently large to jeopardize mission success. The maximum penalty ever likely to be encountered on Apollo-type lunar missions is approximately 0.5 percent or less when compared to an absolute optimum.

It had been noticed from some external-ΔV, fixed-attitude LOI studies that a fixed-attitude burn always results in the altitude difference between the lunar orbit and approach hyperbola at their common node being equal to zero (Fig. 3). While external ΔV has fixed attitude as an explicit part

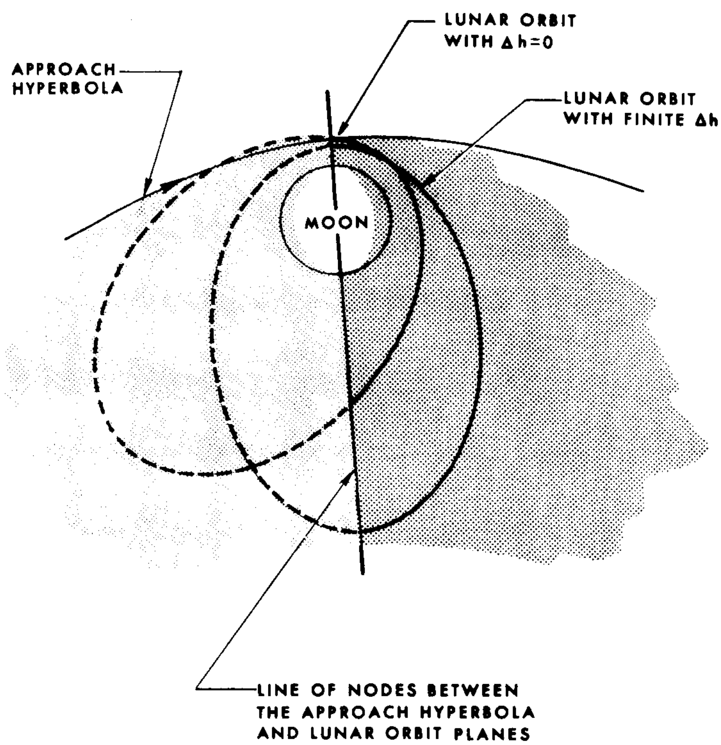

Figure 3. Nodal altitude between the approach hyperbola and the lunar orbit, Δh.

of the guidance, this is not so for Lambert. Lambert guidance constants can be selected to burn into lunar orbits with varying nodal altitude differences between the lunar orbit and approach hyperbola. The burn pitch and burn yaw profiles vary from burn to burn, depending on the geometry and guidance constants. However, targeting a Lambert LOI burn to a lunar orbit with no nodal altitude difference between it and the approach hyperbola gives, for all practical purposes, a fixed attitude burn like external ΔV. Until recently, the capability of retargeting to steer out nodal altitude differences (resulting in a nonfixed attitude burn profile) was an important part of the LOI target update capability; thus, the fixed attitude constraint is significant. But the constraint results in a simplification, to be discussed later, that makes this LOI targeting logic practical for real-time use.

NODE SHIFT AND HYPERBOLA ALTITUDE DISPERSION PROBLEMS

The three major constraints make it difficult to obtain all three of the desired end conditions in the presence of midcourse execution errors and state vector uncertainties for two reasons: (1) a shift of the nodes between the acceptable lunar orbits and hyperbola plane caused by an out-of-plane dispersion (Fig. 4) and (2) a change in the hyperbola altitude at the nodes caused by an inplane dispersion (Fig. 5). The LOI maneuver usually includes a small plane change. This means that small out-of-plane errors at the midcourse can cause the nodes between the acceptable lunar orbits and the approach hyperbola to shift easily to unacceptable positions in terms of altitude and/or LOI fuel required. Inplane errors at midcourse execution can cause a change in the nodal altitude even if the nodes stay in the same inertial position in space.

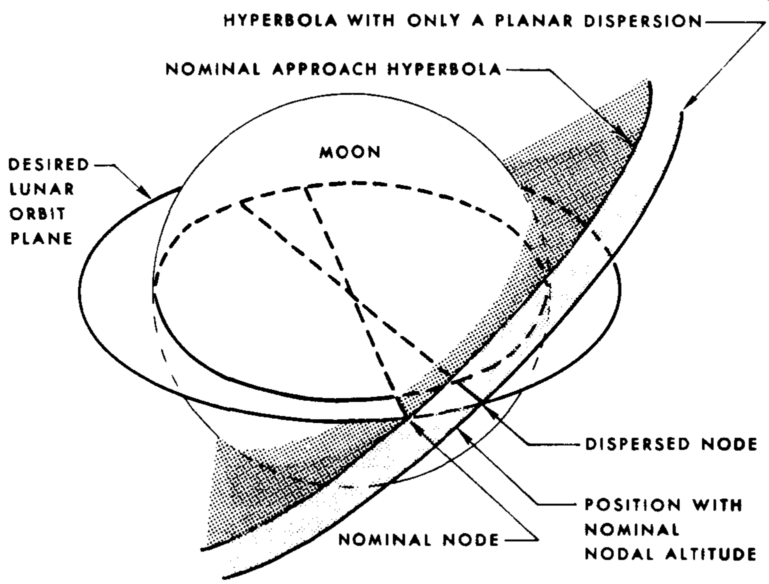

Figure 4. Node shift dispersion.

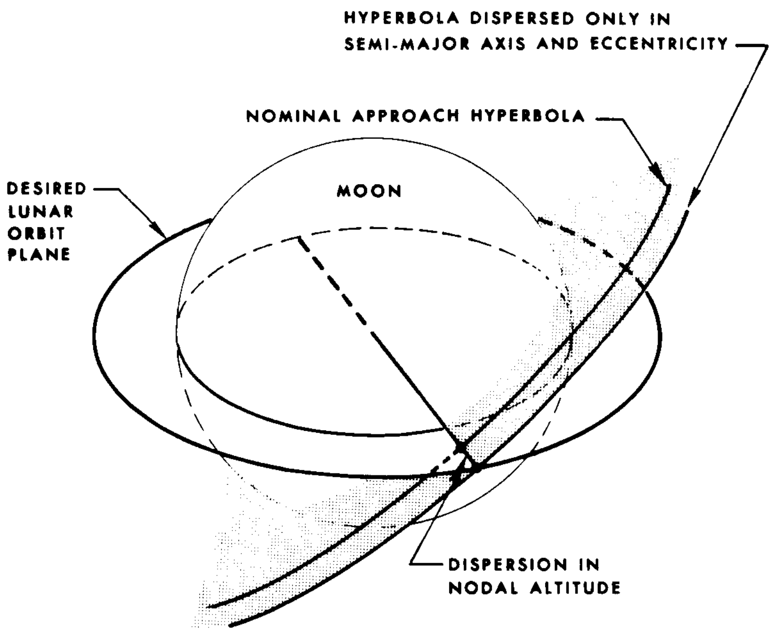

Figure 5. Nodal altitude dispersion.

If yaw steering capability were available in the guidance, the node shift would present less of a problem than it does. Since, nominally, LOI occurs near perilune of the hyperbola, the node will usually shift to a larger flight-path angle, thus resulting in a larger ΔV to burn around the node into the desired lunar orbit. Consequently, the LOI target update capability is limited as to the magnitude of out-of-plane dispersions it can absorb because of the tight performance constraints.

If there were inplane midcourse dispersions such that the nodal altitudes were lower than the desired lunar orbit perilune altitude, a burn at fixed attitude could not be performed because there would be an altitude difference between the lunar orbit and approach hyperbola at the node. Without the fixed attitude constraint, small nodal altitude differences could be steered out.

The preceding discussion was intended to present an important point - namely, that situations can exist where the mission is proceeding within reasonable limits, but not all the LOI target objectives can be met with an LOI target update. Thus, for these situations, the LOI targeting logic must provide a solution which optimally compromises the miss in the target objectives in such a way that the mission can proceed.

DETERMINATION OF A LUNAR ORBIT THAT BEST SATISFIES THE TARGET OBJECTIVES

Because there are situations when all of the desired target objectives cannot be achieved, some of the target objectives must be relaxed or violated if the mission is to continue. However, it is extremely difficult to determine premission which objectives can be violated and still result in an acceptable lunar orbit. On some launch days, when more fuel is available than necessary, the performance constraint is not as severe and more ΔV than planned may be spent for LOI. Sometimes the node shift problem can move the nodes between the approach hyperbola and acceptable lunar orbits so far that it is not practical to burn around any of the nodes. Then, the landing site objectives must be violated. At other times, the inplane altitude dispersions force the lunar orbit shape objective to be violated in order to pass over the landing site with an acceptable azimuth. And, of course, there are couplings among these considerations. The main point is that the decision as to which objectives must be violated is dependent on the real-time situation - when the mission is being flown and what has occurred up to the time of LOI. Consequently, it is difficult to program a computer to make the real-time decision on what to give up; this is where the man in the loop, the flight controller, becomes a significant component of the targeting system.

Ten different maneuvers, each defining a particular lunar orbit by giving up a particular target objective, are computed and displayed to the flight controller. The flight controller decides which maneuver will give the best results or what changes to make to the desired target objectives based on the situation at that time. These 10 maneuvers are the solutions to the LOI targeting problem for the Apollo Program.

The 10 solutions are divided into three groups of three maneuvers each plus one single solution. These groups are called the basic, the lunar shape, and the lunar landing site solutions.

The single solution is a maneuver that results in the desired lunar orbit shape in the plane of the approach hyperbola with a minimum ΔV expenditure. Landing site objectives are probably not satisfied. This single solution allows the flight controller to target a coplanar, alternate-mission LOI burn with no landing site constraints.

There are three basic solutions. The first solution passes over the landing site with the maximum allowable azimuth, the second has the preferred azimuth at the site, and the third has the minimum allowable azimuth at the site. These solutions meet the desired landing site conditions at the expense of the lunar orbit perilune altitude if necessary. There is no limitation on the LOI ΔV that may be spent in these three maneuvers. These basic solutions provide the flight controller with the bounds of the problem, and bracket what would be required to return to nominal or meet acceptable end conditions if these solutions are possible.

Lunar orbit shape solutions are those that meet the desired lunar orbit shape constraint (apolune and perilune altitudes) at the expense of other objectives if necessary. There are three of these solutions. The first is the minimum LOI ΔV that passes over the landing site with an acceptable azimuth, thus achieving acceptable end conditions. However, the performance penalty could be unacceptable because of the effect on lunar orbit maneuvers and transearth injection. This minimum LOI ΔV solution is the most practical way to determine which of the acceptable landing site azimuths should be selected.* The second solution also achieves acceptable target objectives but, in addition, comes as near as possible to the preferred azimuth at the landing site within a maximum allowable LOI ΔV input by the flight controller. Again, the performance penalty may be unacceptable. The third solution obtains the lunar orbit shape and comes as near as possible to an acceptable lunar orbit plane within the maximum allowable LOI ΔV. The latter solution will not pass over the landing site. Since the node shift appears to be the most severe problem, this solution will be computed if all objectives cannot be achieved within the flight controller input ΔV constraint. The first and second solutions may not always physically exist and thus would not be displayed, but the third solution will always exist if the maximum allowable LOI ΔV constraint is greater than the ΔV necessary for a coplanar burn.

Lunar landing site solutions, the third group of solutions, pass over the landing site with an acceptable azimuth at the expense of the lunar orbit perilune altitude. There are three solutions in this group. The first is the minimum LOI ΔV for which acceptable landing site conditions are met (with the lunar orbit perilune altitude equal to the nodal altitude). The second meets the landing site objectives and also comes as near as possible to the preferred azimuth at the site within the maximum allowable LOI ΔV (again with the lunar orbit perilune altitude equal to the nodal altitude). The third solution meets the landing site objectives and comes as near as possible to the desired lunar orbit perilune altitude. This group can only exist when there is an altitude on the approach hyperbola lower than the desired lunar orbit perilune altitude. Some solutions may be the same. For example, the landing site solution nearest to the preferred azimuth could be the basic solution corresponding to the preferred azimuth if the input LOI ΔV constraint was large enough.

As with the lunar orbit shape solutions, the performance penalties of the landing site solutions could be unacceptable since LOI ΔV is not

*A maximum end-of-mission fuel reserve is really the best way to do this, but this type of solution is not computed for reasons to be discussed later.

traded off against the other planned spacecraft maneuvers to maximize the fuel at the end of the mission. There are two reasons why this trade-off is not done.

1. It was previously performed preflight and, if necessary, in the midcourse targeting processor. A reasonable midcourse should set up an LOI maneuver with nearly optimum fuel reserves. This reasonable midcourse is expected; if it were not, a solution to maximize fuel would be computed.

2. The computation requires a sophisticated iteration to compute transearth injection; it was desired to avoid this iteration. These reserves are not expected to be unacceptable, but data have shown that there are significant effects when the lunar orbit orientation is redefined and the burn to circularize the elliptical lunar orbit does not occur at perilune. Thus, the fuel must be checked to insure that an LOI maneuver is not selected that could jeopardize crew safety or mission success.

Since the LOI ΔV for each particular solution is not traded off against the rest of the maneuvers, a performance limit must be set in the program to avoid using all the spacecraft fuel in LOI. This limit is the maximum allowable ΔV for LOI mentioned before, and its value can be increased or decreased by flight controller request. The limit keeps the LOI maneuver within reasonable bounds and is the best practical way to determine how much any target objectives may be violated. It is obvious that choosing and changing the value of the maximum allowable LOI ΔV in real time will be difficult. Thus, here is one of the places that the bounds of the LOI problem provided by the single, coplanar solution and the basic solutions become valuable.

The flight controller also has the option of asking the logic to target LOI burns to other than the nominal target objectives. This is necessary for real-time flexibility. The flight controller may request a lunar orbit of different shape by an apolune and/or perilune altitude input. The flight controller may change the range of allowable azimuths and the preferred azimuth at the landing site but may not change the landing site position (latitude and/or longitude). Thus, the flight controller may change the desired values for all the end conditions except the landing site position. However, he cannot relax the simple guidance laws and fixed attitude constraints.

Since the fixed attitude constraint cannot be relaxed, it is possible to make a simplifying approximation that makes the LOI targeting logic practical for real-time use. It was noted earlier that fixed attitude LOI maneuvers, required for crew monitoring, meant that the altitude of the lunar orbit and hyperbola at their common node must be equal. Analysis has shown that this latter characteristic allows the LOI maneuver to be acceptably simulated by an impulsive ΔV computation at the common node.

This impulsive approximation is acceptable in two respects. First, the impulsively computed ΔV approximates the finite burn ΔV with sufficient accuracy to allow meaningful comparisons and trade-offs in targeting. Second, a finite burn can be satisfactorily superimposed on the impulse; that is, the guidance constants can be calculated to steer a maneuver around the impulsive point, burning out on the impulsively defined lunar orbit within acceptable tolerances.

Use of this impulsive burn simulation makes two tests necessary prior to the computation of the solutions. First, the approach hyperbola must have a perilune altitude less than the desired lunar orbit apolune altitude. If this is not so, the impulsive simulation cannot be applied, since an impulsive transfer point into the ellipse of the desired shape does not exist. Second, the maximum allowable ΔV for LOI must be greater than the minimum ΔV necessary for a coplanar LOI. Thus, the solution for minimum ΔV burn to the lunar orbit of the desired shape must be generated to make this test.

With this simplification of the impulsive burn, two degrees of freedom are left in the problem: the impulsive plane change and the impulsive maneuver point. The first degree of freedom discussed will be the plane change - assuming for the moment that the impulsive point is given. First, it is necessary to relate the landing site conditions of latitude, longitude, and minimum and maximum allowable azimuth to conditions at LOI. When this is done, the plane change necessary at LOI to achieve certain landing site conditions, or misses of landing site objectives within the plane change capability of the maximum allowable LOI ΔV, can be calculated by simple plane geometry.

The relationship between landing site and LOI conditions is determined by the use of a variable called θ which is defined as follows. Two selenographic lunar orbits are defined at the landing site by the latitude, longitude, and minimum and maximum azimuths (Fig. 6). The two planes specified by the minimum and maximum azimuths encompass all acceptable lunar orbit planes at the site; and the unit normals (angular momentum vectors) to these minimum and maximum planes encompass, in the plane between them, all acceptable unit normals. At a time defined by the midcourse processor, these two planes are converted to inertial coordinates and are propagated back to the time of LOI as predicted by the midcourse processor. This backward propagation is performed with an orbit-predictor routine which accounts for the perturbations to two-body motion. For the purpose of the discussion, the unit normal to these two lunar orbits at LOI are called $\hat{U}_{mn}$ and $\hat{U}_{mx}$. The same situation now exists at LOI as the landing site; all acceptable lunar orbit unit normals (that is, unit normals to lunar orbit plane that will pass over the landing site within the defined

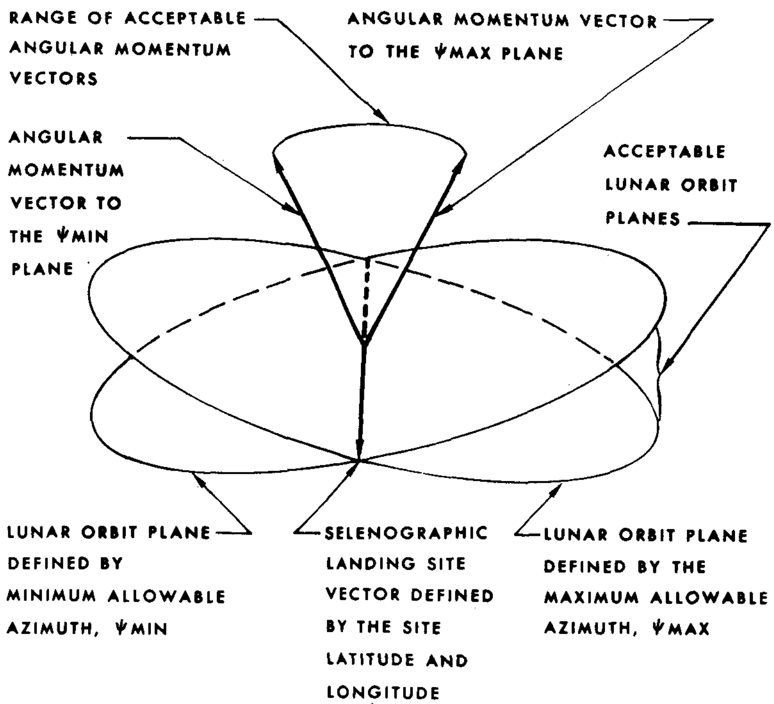

Figure 6. Acceptable lunar orbit geometry at the landing site.

azimuth range) are contained in the plane between $\hat{U}_{mn}$ and $\hat{U}_{mx}$.** Thus, θ can be defined (Fig. 7) as the angle between the actual lunar orbit unit normal and the nearest acceptable unit normal. Acceptable landing site conditions require that θ be zero. Theta combines the landing site objectives into one variable. Nothing is compromised to do this, since if the landing site is missed, the azimuth is of no concern and vice versa.

This backward propagation from known end conditions either to find initial conditions or to first guess initial conditions has been, and is, used on other targeting systems. The Lunar Orbiter Project targeting logic propagated a lunar orbit back from the first photo target to the deboost time to establish a desired deboost target orbit. The midcourse correction processor used in the Apollo Program uses a backward patch conic from the moon to the translunar trajectory to compute targets for a midcourse burn. However, the above methods find only the initial conditions for one particular set of end conditions. The backward lunar orbit

**There are obviously errors associated with this assumption. However, analysis has shown these errors to be less than 0.001° and 0.002° and thus negligible.

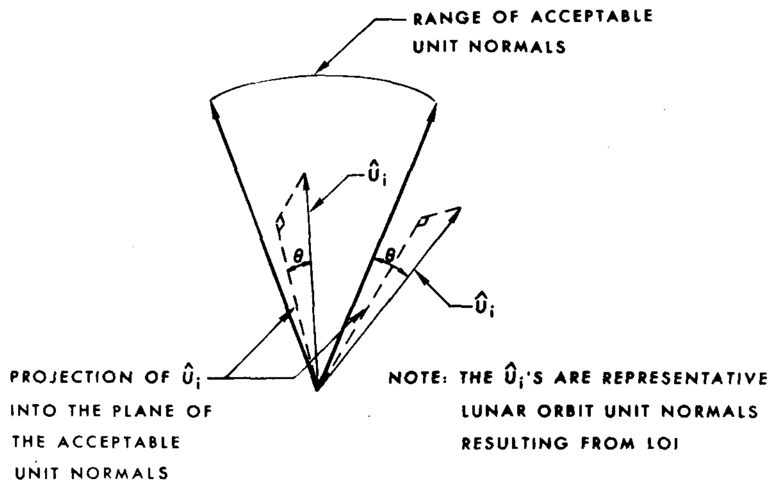

Figure 7. Definition of θ.

propagation used in Apollo LOI targeting extends this concept so that initial conditions may be easily and accurately computed for many sets of end conditions (namely the various azimuths at the landing site).

The unit normals $\hat{U}_{mn}$ and $\hat{U}_{mx}$ form two sets of nodes on the approach hyperbola, but only one of these two sets of nodes will be used. The true anomalies on the hyperbola associated with the extremes of the selected node range are η_{mx} and η_{mn}. A plane change may be calculated by plane geometry at any impulsive point within η_{mn} and η_{mx} to make θ equal to zero. A particular impulsive point radius vector determines a normal vector to a plane in which all unit normal vectors to impulsively defined lunar orbit planes at the particular impulse point must lie. Since $\hat{U}_{mn}$ and $\hat{U}_{mx}$ form a plane, the intersection of the plane defined by a particular impulsive point radius and the $\hat{U}_{mn}$ and $\hat{U}_{mx}$ defined plane determines a line. If this line lies between $\hat{U}_{mn}$ and $\hat{U}_{mx}$ (that is, if a particular impulsive point is between η_{mn} and η_{mx}), the plane change at LOI to make $\theta = 0.0$ and the landing site azimuth resulting from that plane change can be calculated (Fig. 8). Also, given the desired lunar orbit apolune and perilune altitudes, the impulsive point altitude, and the allowable LOI ΔV, the allowable plane change within the ΔV constraint may be computed. This allows the calculation of the misses in landing site objectives within the maximum allowable LOI ΔV if the objectives cannot be obtained.

If the true anomaly is not between η_{mn} and η_{mx}, a minimum θ miss can be calculated by finding the minimum distance between two portions of two planes. One of these portions is defined by the amount of plane change that can be made at the impulsive point within maximum allowable ΔV while the other is defined by $\hat{U}_{mn}$ and $\hat{U}_{mx}$ (Fig. 9). Finding the

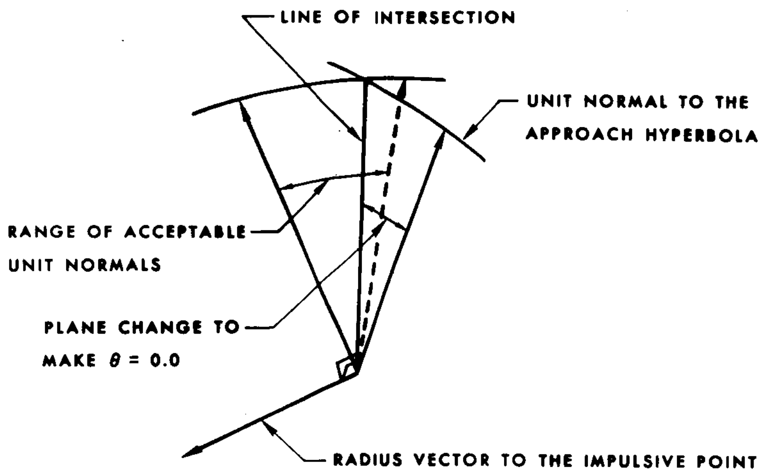

Figure 8. Plane change to make θ equal to zero.

minimum distance will give a lunar orbit unit normal corresponding to a minimum θ. Then θ may be calculated as shown in Figure 7. These two plane segments may have many different positions relative to each other. Calculating a minimum distance between the two segments (and therefore a minimum angle θ) requires determining their relative positions; from that point it is simple to find the vectors in both planes that are nearest each other.

The remaining degree of freedom is the position of the impulsive point. The selection of the impulsive point for the various categories of solutions is accomplished by the use of a finely meshed scan along the hyperbola as follows. The translunar trajectory is integrated to perilune of the approach hyperbola; from there it is propagated back conically along the hyperbola to the preperilune altitude which is equal to the desired apolune altitude. The scan begins at this point, proceeds forward through perilune, and terminates at the postperilune altitude which is equal to the desired apolune altitude. These scan limits bound the entire region where impulsive maneuvers can be performed from the hyperbola to a lunar orbit with the desired apolune altitude.

Discrete state vectors are computed through the scan. At each position,

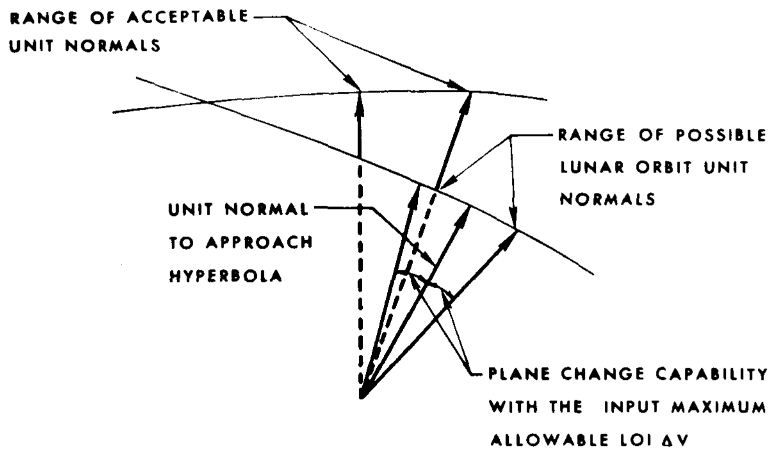

Figure 9. Typical geometry when a minimum θ must be calculated.

three key questions are asked. (These questions form the major tests in the LOI targeting logic.) Is the altitude greater than the desired lunar orbit perilune altitude? Is the true anomaly between η_{mn} and η_{mx}? Is the ΔV of the impulsive maneuver greater than the maximum allowable LOI ΔV? These questions determine what solution or solutions can be calculated at the particular impulsive position. For example, if the altitude of the particular point is less than the desired perilune altitude, the three lunar orbit shape solutions cannot be computed at the particular position because of the fixed attitude constraint. However, if the altitude were greater than the desired perilune altitude, the lunar orbit could be rotated so as to give no altitude difference, since the lunar orbit line-of-apsides position is not a target objective (Fig. 3). If the true anomaly is not between η_{mn} and η_{mx}, it is physically impossible to target a burn to pass over the landing site with an acceptable azimuth because of the no-yaw steering limitation of the guidance. Thus, no landing site solutions could be calculated at this particular position, nor can any lunar orbit shape solutions passing over the landing site with an acceptable azimuth be computed.

As the scan progresses, the possible solutions are calculated at the discrete impulsive points. The target objectives that are violated (for example, if the altitude if an impulsive point were smaller than the desired perilune altitude, the perilune altitude objective would be violated) determine which of the remaining nine solutions have been calculated. (The single solution, minimum ΔV coplanar burn has already been calculated.) The violated objective is then tested against the stored solution that violated that same objective. If the new solution is closer to the desired objective, it is retained and the previously stored solution is discarded.

Because all solutions (except the minimum ΔV, coplanar one) are computed during the scan, it is unnecessary to provide the flight controller with the option of which types of solutions to calculate.

At this point, the solutions are displayed to the flight controller. The flight controller selects a solution, changes the asked-for target objectives and reruns the LOI targeting logic, or decides on another midcourse maneuver. Examples of flight controller actions are presented in the last section of this paper.

COMPUTATION OF THE GUIDANCE CONSTANTS

After a solution has been selected, the last step is to calculate the integrated burn that results in the impulsively defined lunar orbit. The guidance constants used to produce this burn are those to be sent to the spacecraft. This burn is found by a powered-flight iterator, that is, a program that simulates the LOI burn, adjusting the guidance constants to satisfy the desired end conditions.

The iterator minimizes a sum of weighted squares of residuals. These residuals are formed by differencing the values of the end conditions obtained by a particular burn and the desired values defined by the impulsive lunar orbit shape, plane, and orientation. A matrix of partial derivatives relates the control variables to the end conditions. An inhibitor function is used to control the size of the weighted correction to prevent a divergence.

FLIGHT CONTROLLER DISPLAYS AND PROCEDURES

This section presents four examples of flight controller displays and subsequent action. Two examples illustrate action to select a particular solution. The third example illustrates action to change the maximum allowable LOI ΔV; the last example illustrates the choice of a midcourse maneuver before LOI. For simplicity, no landing site solutions or end-of-mission fuel reserves are shown. Since no landing site solutions are shown, the desired lunar orbit shape is obtained for all the examples. Some terminology should be defined here. Preferred target objectives refer to the preferred azimuth at the landing site, and acceptable target objectives refer to any acceptable landing site azimuth. Table I defines the symbols used. Table II lists important parameter values for the nominal burn and the flight controller inputs to the logic.

TABLE I. SYMBOLS

Symbol	Definition
ΔV	LOI velocity change, fps
h_N	Altitude of the lunar orbit/hyperbola node, n. mi.
ψ	Azimuth of the lunar orbit at the landing site, deg
θ	Wedge angle between the lunar orbit plane and the nearest acceptable lunar orbit plane, deg
δ_{op}	Angular distance of the lunar orbit from the landing site at the point of nearest approach to the site, deg

TABLE II. PARAMETER VALUES

ΔV, fps	3030
Preferred ψ, deg	270
Minimum allowable ψ, deg	265
Maximum allowable ψ, deg	275
Maximum allowable ΔV, fps	3050

Table III shows one of the solutions displayed to the flight controller (for simplicity, others are not shown). The flight controller sees that he can obtain all the preferred target objectives for a ΔV of 10 fps over the nominal 3030 fps. If the end-of-mission fuel is acceptable, he selects this solution.

TABLE III. TYPICAL SOLUTION, RETURN TO NOMINAL

ΔV	h_N	ψ	θ	δ_{op}
3040	65.0	270.0	0.00	0.00

Table IV is the pertinent information displayed to the flight controller for five solutions - the three basic and two lunar orbit shape solutions. By looking at the three basic solutions first, the flight controller sees from solution 2 that it costs 25 fps over nominal to obtain all the preferred target objectives. By looking at the lunar orbit shape solutions, he sees from solution 1 that the minimum LOI performance penalty to obtain acceptable target objectives is 5 fps over nominal with an azimuth at landing 5° from the nominal azimuth of 270°. (For simplicity in this example, this is the same as basic solution 1; this is not necessarily so in actuality.) Solution 2 shows the flight controller that the nearest he can come to the preferred azimuth within the maximum allowable ΔV is 2°. Thus, he has the problem bounded; he knows he can obtain the preferred target objectives and for what performance penalty; he knows how cheaply he can do LOI, and how close he can come to all of the preferred target objectives within his maximum allowable ΔV. Thus, he trades off ΔV and target objectives, depending on the mission up to that time. He could also rerun the case with different inputs as in the next example.

Table V shows the pertinent information displayed to the flight controller for the three basic solutions and two lunar orbit shape solutions. By looking at the basic solution number 2, the flight controller sees that he has a 45-fps penalty to obtain the preferred target objectives. This happens because the node has moved to a higher flight-path angle (as shown in the h_N column). Further, from lunar orbit shape solution 1, he sees that the minimum ΔV for acceptable target objectives is 3035 fps. However, he sees from lunar orbit shape solution 2 that by expending only the maximum allowable ΔV, he can come to within 0.1° of an acceptable lunar orbit plane and 0.05° of the landing site. Thus, he reruns the problem with a lower maximum allowable ΔV to see if the out-of-plane miss stays small enough to be an acceptable maneuver.

TABLE IV. SELECTING A COMPROMISE SOLUTION

Solutions	ΔV	h_N	ψ	θ	δ_{op}
Basic solutions					
1	3035	62.0	265.0	0.00	0.00
2	3055	70.0	270.0	.00	.00
3	3065	75.0	275.0	.00	.00
Lunar orbit shape solutions					
1	3035	62.0	265.0	0.00	0.00
2	3050	68.0	268.0	.00	.00

TABLE V. CHANGING THE MAXIMUM ALLOWABLE ΔV

Solutions	ΔV	h_N	ψ	θ	δ_{op}
Basic solutions					
1	3100	100.0	265.0	0.00	0.00
2	3075	75.0	270.0	.00	.00
3	3065	65.0	275.0	.00	.00
Lunar orbit shape solutions					
1	3065	65.0	275.0	0.00	0.00
2	3050	65.0	274.0	.10	.05

Table VI illustrates the use of the LOI targeting logic early in the mission (for example, after translunar injection). The basic solutions show that the trajectory geometry is not acceptable. For the 265° azimuth, an impulsive maneuver cannot even be computed since the nodal altitude is greater than the 170-n. mi. lunar orbit apolune altitude. The ΔV for the 270° and 275° azimuths is unacceptably large. The first lunar orbit solution shows the minimum ΔV penalty to obtain acceptable target objectives is 120 fps. The second lunar orbit shape solution shows that a lunar orbit missing the landing site by 2° results when only the maximum allowable ΔV is expended. Therefore, a midcourse correction is necessary.

TABLE VI. SELECTING A MIDCOURSE CORRECTION

Solutions	ΔV	h_N	ψ	θ	δ_{op}
Basic solutions					
1		220.0	265.0	0.00	0.00
2	3200	165.0	270.0	.00	.00
3	3150	120.0	275.0	.00	.00
Lunar orbit shape solutions					
1	3150	120.0	275.0	0.00	0.00
2	3050	75.0	275.0	3.00	2.00